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Optimally Stationing Army Forces

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There are over one million United States active-duty Army, Army National Guard, and Army Reserve soldiers. The Army assigns each soldier to a unit at one of over 4,000 worldwide locations; these facilities consist of approximately 15 million acres and 287 million square feet. The Army can change a soldier's unit assignment; it can also move a unit's home installation. This paper presents an integer linear program, Optimally Stationing Army Forces (OSAF), which prescribes optimal Army stationing for a given set of units. OSAF uses the existing starting locations, set of installations, available implementation dollars, and unit requirements for facilities, ranges, and maneuver land. It has provided the Army with stationing analysis for several years. Perhaps most significantly, OSAF helped with the closure and realignment decisions during the 2005 round of Base Realignment and Closure (BRAC). As a result of this BRAC, by 2011 the Army will close 400 installations (13 installations that primarily house active-duty soldiers, 176 Army Reserve centers, and 211 National Guard armories) and realign 56 active units. These BRAC actions will impact 43 states, cost more than $13 billion to implement, and generate an expected 20-year net savings of $7.6 billion.

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The United States Army is a large, dynamic organization. It consists of over one million active-duty, Army National Guard and Army Reserve soldiers, and over 500,000 Army civilians and contract service employees. Figure 1 shows the locations of major active-duty Army maneuver installations. Each installation is home to at least 10,000 soldiers and their families, and has all the characteristics and infrastructure of a small city, including housing. The Army divides its housing by rank (e.g., enlisted or officer) and by family category (e.g., accompanied or unaccompanied by family). Table 1 provides some infrastructure statistics for Fort Benning and Fort Drum. In 2005, there were over 4,000 Army Guard and Reserve centers in the United States. In contrast to the active-duty Army maneuver installations, many of these centers consist of a single building.

The Army assigns each active-duty soldier to a unit that it identifies uniquely using a unit identification code (UIC). An Army force structure is the number, size, and composition of its units, including personnel and weapon systems. The Army frequently adjusts the stationing of its force structure as weapon systems, missions, and operations change over time, much as a large corporation modifies its plant infrastructure as product demand and technology change. A stationing analysis is analogous to a location analysis; both examine a firm's requirements, assets, supply chain, and other considerations. Optimization models have long played a key role in developing these corporate plans (e.g., Brown et al. 2001). The Army also has long used integer linear programming to help make stationing decisions. Dell et al. (1994), Dell (1998), and Loerch et al. (1996) describe some early work.

On any given day, the Army has hundreds of units that it plans to move to meet new stationing requirements. Optimal Stationing Army Forces (OSAF), an integer linear program, has informed some of these decisions. This paper describes OSAF with emphasis on its role in helping the Army make its 2005 BRAC recommendations.

OSAF Overview

OSAF prescribes an optimal Army stationing plan for a given force structure. It uses the existing starting locations, set of installations, and available implementation dollars; it also uses stationing restrictions, such as "the National Training Center is fixed at Fort

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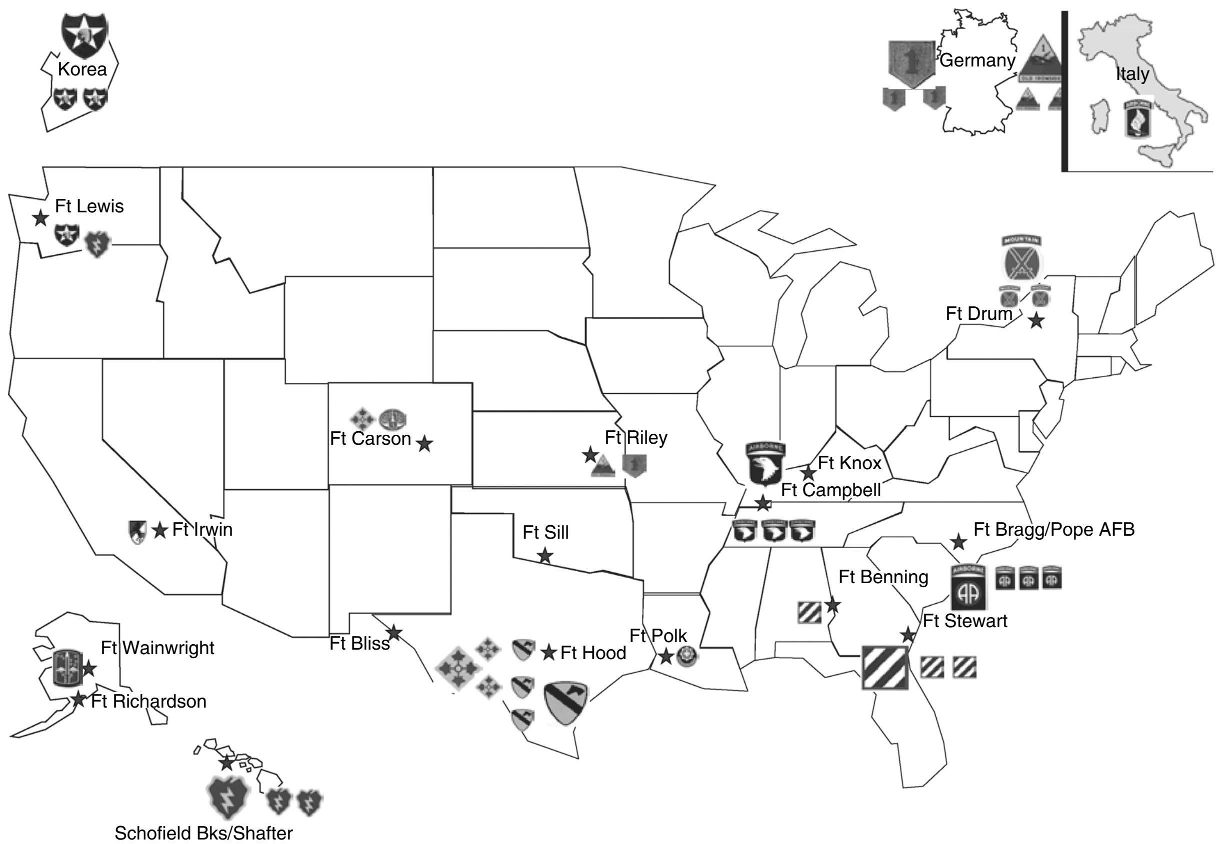

Figure 1: This map shows the major Army maneuver installations in the United States as of 2005. These installations are home to 470,000 soldiers and their families and the workplace for another 233,000 Army civilians. A soldier's home station (installation) could change frequently. Typically, soldiers are assigned to a new unit every two or three years, and the Army frequently adjusts the home station of a unit as weapon systems, missions, and operations change over time.

Irwin," "the Old Guard is fixed at Fort Myer or Fort McNair," and "ensure Apache helicopter training is restricted to Forts Bliss, Carson, and/or Hood" (Connors et al. 2001, Appendix J). The appendix contains a sample OSAF formulation. Each stationing plan must satisfy many unit requirements, such as availability of buildings, land for maneuver training, and ranges necessary to train a unit. The Army uses a set of quantitative and qualitative metrics to evaluate each stationing plan. Reviews by Army leadership over many years have helped analysts to decide which stationing restrictions, unit requirements, and quantitative metrics to include, which to set aside, and which comparisons to leave for posterior expert judgment; in making these decisions, we must frequently balance trade-offs between detail and tractability.

Where to locate facilities is a critical, widely studied strategic decision in both the private and public sectors. Owen and Daskin (1998), ReVelle and Eiselt (2005), and ReVelle et al. (2008) present extensive surveys. OSAF is unique in many ways. Most prior models do not consider an existing set of installation and the explicit cost to change them to a new set. Most consider some facility capacities; however, none considers as many different types of facilities as OSAF includes. OSAF is also unique in its explicit consideration of facility conditions and the need to conditionally upgrade substandard facilities.

OSAF Installations and Units

The Army categorizes its installations into 13 types by primary mission. OSAF addresses the five types

Infrastructure (units)	Fort Benning	Fort Drum
General purpose instruction building (square feet)	455,000	12,000
Applied instruction building (square feet)	68,000	4,000
Organizational classroom (square feet)	202,000	44,000
Aircraft maintenance hangar (square feet)	175,000	283,000
Vehicle maintenance shop (square feet)	398,000	529,000
General administrative building (square feet)	612,000	211,000
Small unit headquarters building (square feet)	608,000	407,000
Large unit headquarters building (square feet)	395,000	236,000
Dining facilities (square feet)	341,000	99,000
Student barracks (square feet)	926,000	0
Recruit/trainee barracks (square feet)	1,457,000	0
Enlisted unaccompanied housing (square feet)	1,450,000	1,234,000
Maneuver training land (acres)	142,126	77,387

Table 1: Fort Benning, Georgia and Fort Drum, New York are two major Army maneuver installations. Each installation is home to more than 10,000 active-duty soldiers and their families. Supporting these soldiers requires substantial installation infrastructure (Department of the Army 2003).

in which most soldiers are stationed: maneuver, command and control, professional schools, major training areas, and training schools. For a typical BRAC 2005 analysis, OSAF must prescribe the stationing for a proposed 2011 force structure that consists of more than 6,000 UICs; this structure includes a military population (military and Army civilians) of approximately 698,000 at 88 installations and training areas, and 11 major leased facilities. OSAF also must consider National Guard and Reserve requirements at these installations.

Considering 6,000 UICs independently within OSAF would make model instances difficult to solve and (if solved) would likely produce unrealistic prescriptions. Many UICs must be located at the same installation for training and other operational reasons. Therefore, the Army aggregated the 6,000 UICs into 655 stationing packages, which OSAF considered as groups for purposes of stationing.

OSAF accounts for the building types and ranges that units require when they are stationed at an installation (i.e., unit requirements). The Army divides its building types and ranges into hundreds of facility analysis categories (FACs), which it inventories in the Army Real Property Planning and Analysis System (Department of the Army 2003). A subset of these FACs provides the majority of the square footage that units require. For example, 25 FACs comprise 80 percent of all square footage of Army buildings, while 50 FACs comprise approximately 90 percent. Most OSAF instances consider 39 FACs aggregated into these nine groups: operations, administrative, aviation maintenance, vehicle maintenance, supply and storage, training instruction (active force), community facilities, unique facilities, and enlisted unaccompanied housing.

The Installation Status Report (Department of the Army 2007) provides a quality rating (green for good, yellow for fair, and red for poor) for each square foot (or other FAC measurement unit) of each FAC at each installation. OSAF combines these groups into "green" and "other" and ensures that any unit moved to a new installation receives green-rated facilities or new construction (it is unreasonable to plan a unit move without having appropriate facilities available). If only other-rated facilities are available for a unit being moved, OSAF applies a cost to upgrade existing facilities to green-rated. OSAF does not upgrade facilities for units whose stationing does not change (i.e., units that do not move) and assumes that units vacate other-rated facilities before they vacate green-rated facilities.

Initial Unit Stationing

The Army has published standards for the amount of each FAC required by each unit. Unfortunately, if we compare the total published standard requirement for all units currently at an installation with what is available at the same installation, we sometimes discover that a shortage exists. In some cases, the shortage might not adversely influence unit operations. In others, it must be corrected; however, BRAC funds cannot finance such a correction.

We considered several straightforward options to model a shortage: (1) lower the standard until all units are in compliance, (2) adjust the standard only for the units at installations that are not in compliance, and (3) require construction at installations to fix any shortfall in any OSAF prescription. The first two options would perpetuate any shortage, even for units that would move to new installations, and would allow a unit to move to an installation that does not have appropriate facilities available. In early versions, OSAF used the third option; later we modeled the imbalance between standards and reality

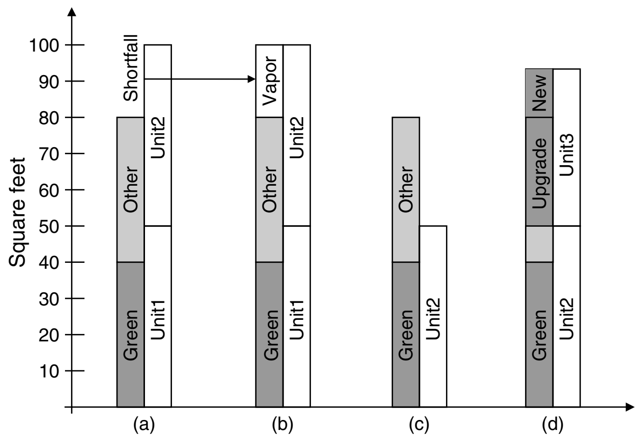

Figure 2: In this example, (a) represents two units (unit1 and unit2) stationed at an installation; each requires 50 square feet of a given type of facility; the installation has 40 green-rated square feet and 40 other-rated square feet available. In (b), OSAF models the shortage using vapor. Provided that the stationing does not change, OSAF allows the shortage to exist. In (c), unit1 moves away, and OSAF assumes it moves out of vapor and then out of other-rated facilities. In (d), unit3 moves to the installation, and must be placed in green-rated facilities; this requires the upgrading of other-rated facilities and new construction.

in much the same way that we model facility conditions (Figure 2). As long as an installation maintains the status quo, addressing an existing shortfall requires no construction; however, a unit that moves requires the standard amount of green-rated facilities space. This provides a prescription that provides each unit no less facility space than it has in the status quo. For implementation, the modification adds an additional facility condition, *vapor*. If there is an existing facility shortage, currently stationed units partially occupy vapor-condition (nonexistent) facilities. Units exit vapor-condition facilities first if they are relocated. Upon being vacated, these vapor facilities are no longer available to units. This allows nonmoving units, but not moving units, to occupy vapor-condition facilities. Richards (2003) reports more on modeling with vapor-condition facilities within OSAF.

OSAF uses maneuver training land and range requirements from Army training circulars (Department of the Army 2004a). OSAF considers two types of maneuver training land: heavy and light measured in kilometer squared days, the measurement that the Army circular uses. We also find some shortages when we compare the total requirement for units currently stationed at an installation and the installation's capacity. The Army cannot typically purchase additional maneuver land; therefore, OSAF allows a user-defined deviation between the requirements of the units stationed and the installation's capacity. There is also a user-defined total deviation across all installations; thus, OSAF can restrict a new stationing prescription, for example, to being no worse than the total status quo. Additionally, it can allow any unused heavy-maneuver land to be used to satisfy light-maneuver land requirements.

OSAF considers the 18 most important range types. Like maneuver land, it allows each range at each installation to have a user-defined shortage and a user-defined total shortage across all installations. In addition, OSAF allows the use of construction to overcome range shortages for a user-defined subset of all range types.

A subset of units can train at installations where they are not assigned, proximity allowing. For this group of installations, we consider the maneuver land and ranges to be common assets available across the installation group.

Costs

Since 1988, the Army and all other Department of Defense organizations have used the Cost of Base Realignment Actions (COBRA) (Richardson and Kirmse 2004) as the mandatory tool for evaluating BRAC costs and savings. COBRA estimates the essential costs and savings of a proposed installation closure or realignment using data that can be assembled without extensive field studies. It is a descriptive model that calculates the net present value (NPV) for a user-defined scenario, which usually consists of only one or two installation closures or realignments. OSAF uses much of the cost data that COBRA uses and follows many of its assumptions.

BRAC analyses must be justified using a 20-year NPV; therefore, OSAF typically minimizes the 20-year NPV cost of stationing a given force structure. It considers both recurring and one-time costs and further divides recurring costs into fixed and variable costs.

Fixed costs occur regardless of the number of soldiers stationed at an installation, and include selected

operating costs for garrison activities (e.g., fire protection and grounds maintenance) and minimum community facilities (e.g., fitness centers and medical facilities).

Each unit stationed at an installation generates a variable cost for installation operations, which we implement as a cost per soldier and a cost per civilian. OSAF uses variable costs from COBRA and Army models that capture the per-person cost of operating each installation, including location-specific facility sustainment, repair and modernization costs, medical costs, and housing operations and allowances.

All unit-stationing actions or installation closures incur one-time costs in military construction (MILCON), transportation, and program management. If an installation receives a unit without sufficient green-rated facilities or range shortfalls, then OSAF assesses a one-time MILCON cost for new construction or to upgrade from other-rated facilities, if such facilities are available.

All unit movements also incur a one-time transportation cost that includes the movement of civilians, equipment, military families, and the military unit.

Evaluating a Stationing Plan

Stationing a force structure is a complex problem; its evaluation requires the use of many criteria, not all of which we can accommodate in a model. Hence, completing a postoptimization review of a proposed plan normally requires the use of the following six metrics (Department of the Army 2005).

- *NPV and investment* is the 20-year NPV of the stationing plan, and the one-time cost for transportation, MILCON, and program management.
- *Military value* reveals a total value of open installations. Ewing et al. (2006) report how the Army determined the military value of each of its installations for BRAC 2005. Using these values, OSAF can maximize military value while restricting the 20-year NPV to a user-defined minimum level.
- *Turbulence* is measured by the number of units moved.
- *Utilization factors* are reported for facilities, ranges, and maneuver land when a low utilization rate could justify mothballing or the demolition of facilities.
- *Impact assessment* is more subjective; it incorporates a review panel's guidance on issues that are difficult to capture, such as strategic implications, quality of life, environment, and ease of mobilization or deployment. Strategic implications represent, mainly from a geographical perspective, the Army's ability to fulfill its mission. For example, the Army cannot station all its forces on one coastline (even if such stationing is cost effective). We examine quality of life using standard Army metrics for an installation and its surrounding community. Environmental assessment includes remediation costs and involves analysis using standard Army models. For unit-deployment and mobilization requirements, we determine if the stationing of a large maneuver force will stress the existing deployment infrastructure (e.g., railheads and airfields) and training infrastructure at the unit's new location.
- *Other* refers to each installation's specific set of "special considerations." If OSAF adds these as constraints, it can determine the cost of imposing them.

Stationing is complex. Solving stationing problems without using models assures that the analyst will find a less-than-optimal result and will have a limited perspective. In contrast, we spend significant time gathering and refining data for OSAF and developing constraints that capture requirements. Once in place, OSAF quickly provides alternatives by, for example, changing the investment that is available to implement a stationing.

Early OSAF Results

From 2000–2002, we briefed senior Army leadership on OSAF results more than 60 times in response to many questions. Below, we list a few questions and some of the insights we gained from OSAF.

Should the Army Consider Stationing Across Installation Types?

The Army categorizes its installations into 13 types by primary mission. In rounds prior to BRAC 2005, the Army only evaluated an installation against the same type of installations (stovepiping); there was little consideration of unit movement across installation types. OSAF results, for the installation types it considered, showed that eliminating the stovepiping restriction could improve savings by up to 30 percent (Connors

et al. 2001). This early observation justified the additional analysis effort that led to no-stovepiping restrictions for the 2005 BRAC round (Department of the Army 2005). Almost all the final, approved BRAC 2005 closures and realignments would not have been possible if stovepiping had been imposed.

Should the Army Wait Until BRAC Decisions Are Announced Before It Starts New MILCON?

The Army did not want to spend millions of dollars on new construction at an installation just prior to closing it. Of course, a few years prior to the approval of the 2005 BRAC round, the Army was unsure of which (if any) installations it would close; therefore, it considered suspending all new MILCON until it could make BRAC decisions. We used various scenarios to compare installations that OSAF frequently recommended for closure to installations with significant new planned construction; the results supported the Army leadership's decision not to suspend MILCON.

How Much Reduction Is Reasonable?

In 2004, the Army determined that its excess facility capacity was 27 percent (Department of the Army 2004b). OSAF analysis showed that for the five installation types that OSAF considers, such a reduction would significantly decrease military value and eliminate substantial required training lands. This analysis helped the Army leadership to conceptualize the consequences of various reduction levels. The final 2005 recommendations, when they are fully implemented, will result in a 5 percent reduction in facilities (Department of Defense 2005).

Where Should the Army Station Units?

The Army often changes the home station of a unit outside of a BRAC round. OSAF has helped with several of these decisions. For example, in 2000 and 2001, it helped the Army to answer questions for the 2001 Quadrennial Defense Review (Tarantino 2003a, b). OSAF suggested potential locations for rotary-wing training (Tarantino 2002); it examined potential new homes for the United States Army Southern Command; and, in 2004 and 2005, the Army used OSAF to support its 2005 BRAC analysis (Ewing and Bassichis 2005).

BRAC 2005 Analysis and Results

The Army's infrastructure decisions are legislatively more encumbered than those of its corporate counterparts. Title XXIX of Public Law 101-510, the National Defense Authorization Act for Fiscal Year 1991, provides a complex and politically insulated process for closing and realigning military installations in the United States. This act established an independent Defense Base Closure and Realignment Commission and set in motion a process, which was called BRAC for 1991, 1993, and 1995, that was to be applied to installations in the United States. The law authorizing these three rounds has been successful in allowing the Department of Defense to eliminate excess infrastructure (Government Accounting Office 2001). Since 1995, the Department of Defense has urged Congress to authorize additional BRAC rounds; it received authorization for the 2005 round in 2002.

Developing the Army's 2005 BRAC recommendations was an extensive undertaking; we estimate that it was more than a 200 person-year effort. In November 2005, the 2005 round of BRAC recommendations became law. These recommendations will help reshape the Army by closing 400 installations (13 installations that primarily house active-duty soldiers, 176 Army Reserve centers, and 211 National Guard armories) and realign 56 active component units. The actions will impact 43 states, cost about $13 billion, and generate an expected 20-year net savings of $7.6 billion. After BRAC completion, the Army expects recurring savings of $1.5 billion annually (Department of Defense 2005).

Army BRAC 2005 closed reserve centers and enabled closure or consolidation of National Guard armories. These closures often involved only a single building and only impacted the local area. Most of this analysis involved first-hand knowledge of the specific buildings in the local area. In contrast, closing or realigning one of the Army's 99 active-duty installations and leases would impact more than its local area. Additionally, the Army was considering the impact of moving units back from Germany and Korea, movement of major administrative activities, and consolidation of primary training centers. For these active-duty closure and realignment actions, it was useful to have a model that would consider the global impact across all installations. OSAF provided

	2003	Total military population	2011	Total military population
Number of UICs	6,263	464,947	6,270	558,140
Number of major units	513	464,947	645	558,140
Number of units from GM (EAST)	N/A	N/A	17	40,683
Number of BASEX (EAST)	N/A	N/A	15	3,654
Number of units from KM (WEST)	N/A	N/A	2	684
Number of BASEX (WEST)	N/A	N/A	17	15,683
Total stationed from EAST/WEST	0	0	51	60,704

Table 2: OSAF primarily considered two force structures for BRAC 2005 analysis: a 2003 baseline and a 2011 projected force structure. For the 2011 force structure, OSAF uses four temporary installations for units without an initial stationing. One of the installations represents a port on the East Coast that would be used for units returning from Germany (GM EAST); one models a port on the West Coast used for units returning from Korea (KM WEST); and two others represent installations on the East Coast (EAST) and West Coast (WEST) for other units that are not currently part of the force structure.

this capability. It gave the Army a model that allowed it to complete many analyses quickly, across many installations, using different force-structure assumptions and resource capacities.

OSAF considered two primary force structures (Table 2): a 2003 baseline and a projected 2011 force structure (Figure 3). BRAC law required the Army and other Services to develop a 20-year force structure plan; the Joint Chiefs of Staff approved the plan and submitted it to Congress. OSAF used the 2011 projected force structure to account for units returning from overseas. We acknowledge that the Army's current force-structure plan differs from the structure that Figure 3 presents; however, the force structure we show, like the rest of the data we present in this section, was the best available from 2003 to 2005; it is also subject to change. A typical OSAF instance consists of approximately 3,000 binary variables, 45,000 constraints, and 70,000 continuous variables. We generate OSAF using GAMS (GAMS Development Corporation 2007) and solve it using CPLEX (GAMS/CPLEX 2007). Generation and solution time is typically less than five minutes.

These two force structures contain three types of combat brigades: (1) heavy unit of action (UA) has approximately 5,300 personnel, with one or two battalions of M1 Abrams tanks and one or two battalions of M2 Bradley fighting vehicles (for a total of three battalions); (2) light UA contains approximately 3,800 personnel, with three light maneuver battalions; and (3) Striker brigade combat team (SBCT) contains approximately 3,500 personnel, with three Striker-equipped battalions.

Based on the data available for the study, the larger installations within the United States have sufficient training land, ranges, and facilities to accommodate five or six combat brigades; however, other factors that OSAF does not consider explicitly, e.g., local infrastructure or other environmental considerations, limit the number of combat brigades that may be stationed at any individual installation. Figure 3 shows these limits within circles.

Using the 2003 force structure (but omitting units returning from Korea and Germany) and varying the one-time implementation costs, we show potential NPV savings of billions of dollars. Each point of the graph in Figure 4 represents an OSAF prescription for a different one-time budget. After the one-time cost reaches approximately $3.8 billion, the rate of savings per one-time cost investment significantly decreases. Figure 5 shows the closures for each prescription on the efficient frontier. Typically, there are a number of installations that are always closed (Figure 5 shows 16 installations), always open (not shown), and several that are open or closed (Figure 5 shows six) depending on the available one-time implementation costs. Installations enter and leave the portfolio (e.g., Installation 22) because of the complex trade-off between value and the capacities that the installations provide. Viewing such an efficient frontier and the corresponding closures became a standard part of an OSAF analysis; therefore, we automated the generation of the efficient frontier.

The impact of a single BRAC decision can be significant and, once put into law, almost impossible to change. Therefore, we designed numerous scenarios to help examine the solution robustness of closure and major unit movement. Focusing only on installation closures using the 2011 force structure, OSAF recommends nine installations that are consistently closed across all scenarios; these include scenarios in which units from Germany and Korea are not forced to return to the United States. Of these nine installations, four are closing and all others are realigning because of the BRAC 2005 recommendations.

We examined the interactions of moving army brigades and the consolidation of large institutional schools. For example, we allow more ranges

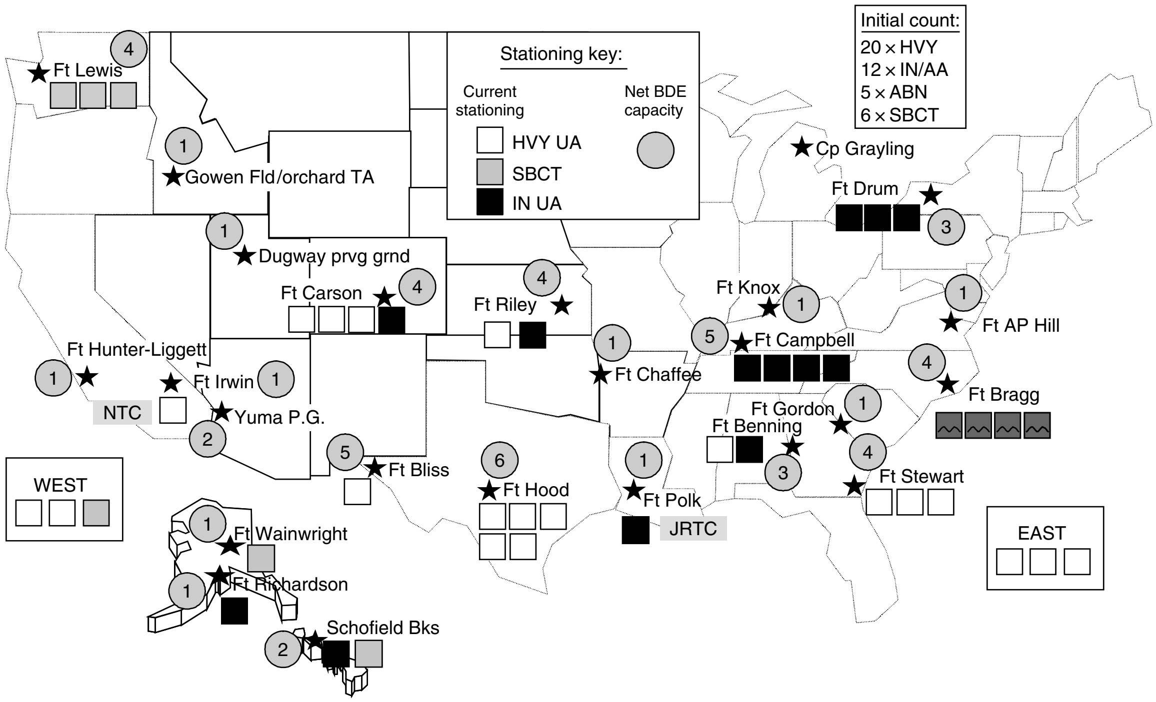

Figure 3: This map shows the initial stationing proposal of 43 combat brigades for the 2011 force structure based on data available at the time of the analysis. Only the installations (both active and reserve Army components and other Service installations) that have the capability to accept an Army combat brigade are displayed. The squares denote the initial stationing of the three types of combat brigades; the circles denote the upper bound of combat brigades allowed at the given installation.

to be built (through relaxation of the range constraint) and force different schools to consolidate at large installations. This analysis supported three major school-consolidation recommendations for BRAC 2005.

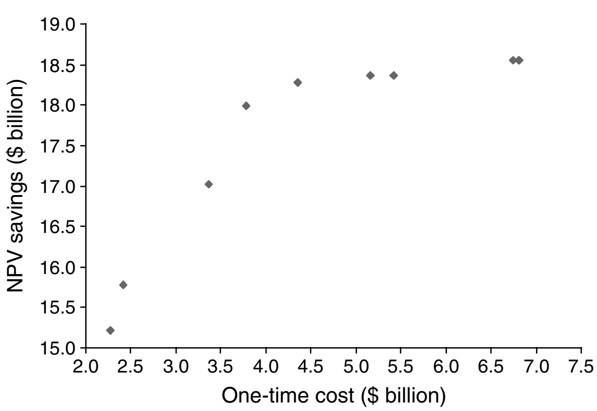

Figure 4: Each point represents an OSAF prescription for a different one-time budget for the 2003 baseline.

Once the set of recommendations for closure and realignment was almost final, we engaged OSAF to address many specific "what-if" questions. Two representative questions were:

1. Does the Army maintain enough capability to station additional maneuver brigades? If so, where are the most likely installations?
2. What impact will the Army BRAC recommendations have on the Army's ability to station one large and two small administrative facilities?

To answer these questions, we used the 2011 force structure; we forced from zero to 16 installations to close to account for the most likely closures. We also forced from zero to 13 major realignments that were likely to occur. We added different combinations of heavy UA, light UA, and SBCT to account for increased force-structure requirements.

OSAF results indicate that training land and ranges are the constraining factors when stationing a new brigade; even with 16 installations closed, the abil-

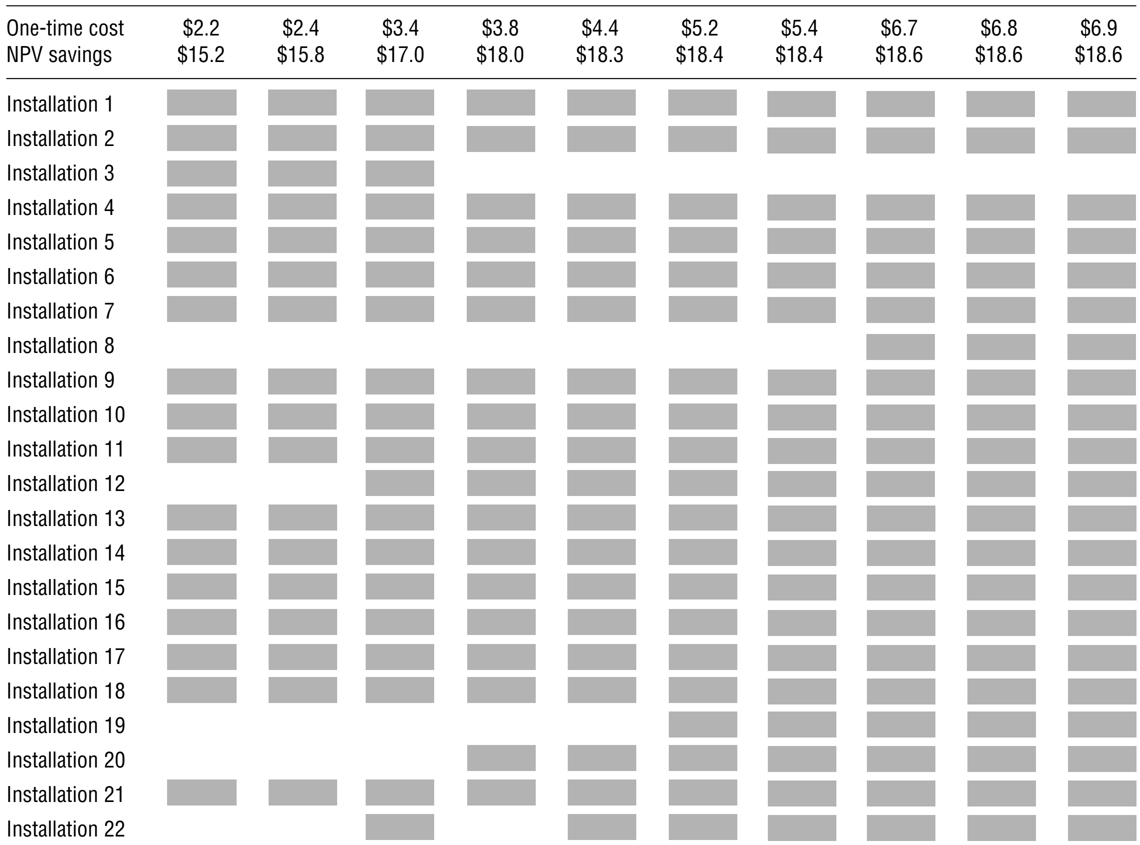

Figure 5: This chart shows installation closures because of changing the allowed one-time budget. It depicts the closures represented at each point on Figure 4; each shaded rectangle represents a closure.

ity exists to station a new brigade. However, the cost is significant when buildings are no longer available. For example, three new brigades (one heavy UA, one light, and one SBCT) would cost approximately $8.4 billion for new construction.

To answer the second question, we stationed two small administrative units (which required 23,000 square feet of space) and one large administrative unit (which required 150,000 square feet). Our results indicate that even with the closure of the previous maximum of 16 installations, sufficient administrative space exists to station a typical large and two small administrative units in the remaining Army inventory.

How About Politics?

In any important and high-impact analysis, politics is a primary concern. Before and during the BRAC 2005 analysis, we were asked (and are still being asked today) how politics influenced the analysis and final BRAC decisions. Regarding the final-decisions issue, politics might have played a part in some of the final BRAC recommendations, although it did not affect how we conducted our analysis. We were able to mitigate perceived political interference primarily through objectivity and transparency. We did not use any constraints to force any decision for political reasons. If the leadership made a decision that contradicted our analysis recommendations, we responded with analysis that highlighted any unintended consequences of that particular decision. By not including arbitrary political constraints, we helped the Army leadership make informed decisions. Moreover, to help others accept the Army recommendations, we relied on transparent modeling and analysis. Transparency was critical to justifying recommendations to the auditing agencies and the BRAC 2005 Commission.

Summary and Conclusions

The Army, like other large organizations, has varying requirements as technology evolves and the size of the organization changes. Even with a small number of alternatives, an Army stationing decision is complex and requires analysis from many perspectives. OSAF addresses the complexity and quickly prescribes an optimal stationing plan for a given set of inputs and stationing restrictions and a set of realistic assumptions.

We have continuously refined OSAF based on reviews by Army leadership and our many analyses, with support from the 2001 Quadrennial Defense Review and, more recently, with the BRAC 2005 analysis.

Developing the data necessary to support such a large-scale decision in reasonable detail requires significant, continuing commitment, and dedicated resources. The Army has made this commitment and, as a result of using optimization, has enjoyed additional benefits:

• All assumptions and constraints for each scenario are documented and stated explicitly. This means that each stakeholder can state a case on a level playing field, with transparency to all others.

• Every optimized plan satisfies the myriad of details expressed in the underlying constraints. This means that valid comparisons between competing plans can be made quickly.

• Every proposed solution is the best that can be achieved under the circumstances. This is a comfort when dealing with contentious decisions that involve huge amounts of our national treasure.

We used OSAF to help analyze the BRAC 2005 stationing of the operational force and analyze the robustness of closure and major unit-movement decisions under numerous scenarios.

Appendix. OSAF Formulation

OSAF is an integer linear program that prescribes optimal Army stationing for a given set of units. It uses the existing starting locations, set of installations, available implementation dollars, and unit requirements for facilities, ranges, and maneuver land. OSAF typically minimizes the NPV cost of implementing closures and realignments and installation operations over 20 years. Maximizing military value is an alternate objective.

We show a sample OSAF formulation using Naval Postgraduate School standard format (Brown and Dell 2007).

Index and Sets Use (∼Cardinality)

c: facility condition {green, other, vapor} [∼3].
f: FAC (facility analysis category) [∼9].
i: installation [∼100].
k: maneuver land type [∼2].
r: range type [∼18].
u: unit [∼600].
$i \in CA_u$: set of installations where unit u can be stationed.
$i \in FIX$: set of installations i that are fixed open.
$u \in IS_i$: set of units currently stationed at installation i.
$r \in N$: set of ranges r requiring construction to satisfy a shortage.
$i \in S$: set of installations i that share the same training assets.
$u \in UA_i$: set of units u that can be assigned to installation i.
$(f, i) \in O$: set of f and i with other-rated facilities.
$(f, i) \in V$: set of f and i with vapor facilities.
$(f, i) \in VO$: set of f and i with vapor but without other-rated facilities.

Parameters

Military value [*units*]

$mvalue_i$: military value of keeping installation i open [value].

Cost [*units*]

fco_i: fixed cost of keeping installation i open [2005 $].
fcc_i: fixed cost to close installation i [2005 $].
fct_u: fixed cost to move unit u [2005 $].
$bmilcon$: budget for military construction [2005 $].
$bmove$: budget for transportation [2005 $].
$bman$: budget for management [2005 $].
$btotal$: total budget [2005 $].
vcm_{fi}: MILCON for facility type f at installation i [2005 $/SF].

vcr_{ir}: cost for a new range r at installation i ($/Range).
vcu_{fi}: cost to upgrade facility type f at installation i [2005 $/SF].
vca_{iu}: variable cost if unit u is assigned to installation i [2005 $].
$vcse_{fi}$: cost to sustain existing facilities type f at installation i [2005 $/SF].
$vcsn_{fi}$: cost to sustain new facilities type f at installation i [2005 $/SF].
vct_{iu}: cost of moving unit u to installation i [2005 $].
$vccv_{ff'i}$: cost to convert facility type f into type f' at installation i [2005 $/SF].

Range [*units*]

$daycapn_{ir}$: range days available for range type r [day].
$km2cap_{ik}$: capacity of type k maneuver land at installation i [KM^{2}day].
$km2req_{uk}$: required type k maneuver land for unit u [KM^{2}day].
$km2short_k$: allowed (existing) type k maneuver land shortage [KM^{2}day].
$daycap_{ir}$: type r range capacity at installation i [day].
$dayreq_{ru}$: type r range required for unit u [day].
$dayshort_r$: allowed (existing) range type r total shortage [day].
$dayIshort_{ir}$: allowed range type r shortage at installation i [day].
$daySshort_r$: allowed range type r shortage for set S [day].
$km2Ishort_{ik}$: type k allowed maneuver land shortage at installation i [KM^{2}day].
$km2Sshort_k$: type k allowed maneuver land shortage for set S [KM^{2}day].

Facility [*units*]

$faccap_{cfi}$: facility type f capacity at installation i in condition c [SF].
$facreq_{fu}$: facility type f required for unit u [SF].
$green_{fi}$: "green"-condition type f facilities not used by currently stationed units at installation i [SF].
$other_{fi}$: "other"-condition type f facilities not used by currently stationed units at installation i [SF].

Adjusted Present Value (*APV*) *Factor Data for Converting to NPV* (*time*)

apvbos: APV for Base Operations Support (BOS) (years 1–20).
apvbosss: APV for BOS for steady-state stationing (years 7–20).
apvbossq: APV for BOS for transition stationing (years 1–6).
apvmilcon: APV for MILCON (years 1–20).
apvmntss: APV for maintenance for steady-state stationing (years 7–20).
apvmaint: APV for maintenance (years 1–20).
apvman: APV for management (years 1–20).
apvmove: APV for transportation (years 1–20).

Decision Variables

The nonnegative decision variables keep track of resources that are used or become available at each installation. They also allow for MILCON, facility upgrades, and FAC conversions.

OSAF uses binary variables to determine if a unit is stationed at an installation, to ensure that relocating units vacate the vapor- and other-condition facilities first, and to determine if an installation is closed.

Nonnegative Variables [*units*]

$DAYADD_{ir}$: deviation for range type r at installation i [day].
$KM2ADD_{ik}$: deviation for maneuver land type k at installation i [KM^{2}day].
$MILCON_{fi}$: MILCON of facility type f at installation i [SF].
$UPGRAD_{fi}$: upgrade of facility type f in "other" condition into "green" condition at installation i [SF].
$RANGE_{ir}$: number of range type r to build at installation i [day].
$AGREEN_{fi}$: green-condition facilities of type f made available by units moved from installation i [SF].
$USEHVY_i$: fraction of heavy-maneuver land in use at installation i.
$CONV_{cff'i}$: conversion of condition c facility type f into type f' green-condition facility at installation i [SF].
VAP_{fi}: vapor space of FAC type f vacated at installation i by exiting unit(s) [SF].

Binary Variables

$STATION_{iu}$: 1 if unit u is assigned to installation i, 0 otherwise.

$CLOSE_i$: 1 if installation i is closed, 0 otherwise.

$EXIT_{fi}$: 1 when units move from all type f other-condition facilities at installation i, 0 otherwise.

$EXVAP_{fi}$: 1 when units move from all type f vapor-condition facilities at installation i, 0 otherwise.

Objective Function (Minimize NPV)

$$
\begin{aligned}
&MINIMIZE\\
&apvbosss\Big(\sum_{i,\,u\in UA_i} vca_{iu}STATION_{iu}\Big)\\
&\quad + apvbossq\Big(\sum_{i,\,u\in IS_i} vca_{iu}STATION_{iu} + \sum_i fco_i CLOSE_i\Big)\\
&\quad + apvbos\Big(\sum_i fco_i(1-CLOSE_i)\Big)\\
&\quad + apvmilcon\Big(\sum_{fi} vcm_{fi}MILCON_{fi}\\
&\qquad + \sum_{i,\,r\in N} vcr_{ir}RANGE_{ir} + \sum_{fi} vcu_{fi}UPGRAD_{fi}\\
&\qquad + \sum_{cff'i} vccv_{ff'i}CONV_{cff'i}\Big)\\
&\quad + apvmntss\Big(\sum_{fi}(vcm_{fi}MILCON_{fi}\\
&\qquad + (vcsn_{fi} - vcse_{fi})UPGRAD_{fi})\Big)\\
&\quad + apvmntss\Big(\sum_{cff'i}((vcsn_{f'i} - vcse_{fi})CONV_{cff'i})\Big)\\
&\quad + apvmaint\Big(\sum_{fi\ \ c\notin\{\text{“}vapor\text{”}\}} vcse_{fi}faccap_{cfi}(1-CLOSE_i)\Big)\\
&\quad + apvmove\Big(\sum_{i,\,u\in UA_i \text{ and } u\notin IS_i} vct_{iu}STATION_{iu}\Big)\\
&\quad + apvman\Big(\sum_i fcc_i CLOSE_i\\
&\qquad + \sum_{i,\,u\in UA_i \text{ and } u\notin IS_i} fct_u STATION_{iu}\Big).
\end{aligned}
$$

The objective function expresses the 20-year NPV cost. NPV is calculated as the total cost in current-year dollars for all the one-time and reoccurring base operating costs in the first 20 years. All costs are multiplied by an appropriate ratio to convert them to NPV.

Objective Function (Maximize Military Value)

$$
\begin{aligned}
&MAXIMIZE\\
&\sum_i mvalue_i(1-CLOSE_i).
\end{aligned}
$$

This additional objective function expresses the total military value of open installations. When using this objective, the previous objective (20-year NPV) is restricted to not exceed a user-defined aspiration level.

Constraints

$$
\begin{aligned}
&\sum_{u\in UA_i} facreq_{fu}STATION_{iu}\\
&\quad \le \sum_c faccap_{cfi} + MILCON_{fi} - VAP_{fi}\\
&\qquad + \sum_{cf'}(CONV_{cf'fi} - CONV_{cff'i}) \quad \forall f, i, \qquad (1)
\end{aligned}
$$

$$
\begin{aligned}
&\sum_{u\in UA_i \text{ and } u\notin IS_i} facreq_{fu}STATION_{iu}\\
&\quad \le AGREEN_{fi} + MILCON_{fi} + UPGRAD_{fi}\\
&\qquad + \sum_{cf'} CONV_{cf'fi} \quad \forall f, i, \qquad (2)
\end{aligned}
$$

$$
\begin{aligned}
&AGREEN_{fi} + UPGRAD_{fi} + VAP_{fi} + \sum_{cf'}(CONV_{cff'i})\\
&\le other_{fi} + green_{fi}\\
&\quad + \sum_{u\in IS_i\ i'\neq i}\ \sum_{\text{and } i'\in CA_u} facreq_{fu}STATION_{i'u} \quad \forall f, i, \qquad (3)
\end{aligned}
$$

$$faccap_{\text{“}vapor\text{”}fi}EXVAP_{fi} \le VAP_{fi} \quad \forall (f,i)\in V, \qquad (4)$$

$$
\begin{aligned}
&UPGRAD_{fi} + \sum_{f'} CONV_{\text{“}other\text{”}ff'i}\\
&\quad \le faccap_{\text{“}other\text{”}fi}EXVAP_{fi} \quad \forall (f,i)\in V, \qquad (5)
\end{aligned}
$$

$$
\begin{aligned}
&UPGRAD_{fi} + \sum_{f'} CONV_{\text{“}other\text{”}ff'i} \le faccap_{\text{“}other\text{”}fi}\\
&\qquad \forall (f,i)\notin V, \qquad (6)
\end{aligned}
$$

$$faccap_{\text{“other”}fi}EXIT_{fi} \le UPGRAD_{fi} + \sum_{f'} CONV_{\text{“other”}ff'i} \quad \forall (f,i) \in O, \tag{7}$$

$$AGREEN_{fi} + \sum_{f'} CONV_{\text{“green”}ff'i} \le (faccap_{\text{“green”}fi} - green_{fi})EXIT_{fi} + green_{fi} \quad \forall (f,i) \in O, \tag{8}$$

$$AGREEN_{fi} + \sum_{f'} CONV_{\text{"green"}ff'i} \le (faccap_{\text{"green"}fi} - green_{fi})EXVAP_{fi} + green_{fi} \quad \forall (f,i) \in VO, \tag{9}$$

$$\sum_{i\in S}\sum_{u\in UA_i} dayreq_{ru}STATION_{iu} \le \sum_{i\in S}(daycap_{ir} + DAYADD_{ir}) \quad \forall r, \tag{10}$$

$$\sum_{u\in UA_i} dayreq_{ru}STATION_{iu} \le daycap_{ir} + DAYADD_{ir} \quad \forall i \notin S, r, \tag{11}$$

$$DAYADD_{ir} \le dayIshort_{ir} + daycapn_{ir}RANGE_{ir} \quad \forall i, r \in N, \tag{12}$$

$$\sum_{i} DAYADD_{ir} \le dayshort_r \quad \forall r \notin N, \tag{13}$$

$$DAYADD_{ir} \le dayIshort_{ir} \quad \forall i \notin S,\ r \notin N, \tag{14}$$

$$\sum_{i\in S} DAYADD_{ir} \le daySshort_r \quad \forall r \notin N, \tag{15}$$

$$\sum_{i} KM2ADD_{ik} \le km2short_k \quad \forall k, \tag{16}$$

$$KM2ADD_{ik} \le km2Ishort_{ik} \quad \forall i \notin S,\ k, \tag{17}$$

$$\sum_{i\in S} KM2ADD_{ik} \le km2Sshort_k \quad \forall k, \tag{18}$$

$$\sum_{u\in UA_i} km2req_{u\text{“HV”}}STATION_{iu} \le km2cap_{i\text{“HV”}}USEHVY_i + KM2ADD_{i\text{“HV”}} \quad \forall i, \tag{19}$$

$$\sum_{u\in UA_i} km2req_{u\text{“LT”}}STATION_{iu} \le km2cap_{i\text{“HV”}}(1 - USEHVY_i) + km2cap_{i\text{“LT”}} + KM2ADD_{i\text{“LT”}} \quad \forall i, \tag{20}$$

$$\sum_{i\in CA_u} STATION_{iu} = 1 \quad \forall u, \tag{21}$$

$$STATION_{iu} \le 1 - CLOSE_i \quad \forall i \notin FIX,\ u \in UA_i, \tag{22}$$

$$\sum_{fi} vcm_{fi}MILCON_{fi} + \sum_{i}\sum_{r\in N} vcr_{ir}RANGE_{ir} + \sum_{fi} vcu_{fi}UPGRAD_{fi} + \sum_{cff'i} vccv_{ff'i}CONV_{cff'i} \le bmilcon, \tag{23}$$

$$\sum_{i}\sum_{u\notin IS_i} vct_{iu}STATION_{iu} \le bmove, \tag{24}$$

$$\sum_{i}\sum_{u\notin IS_i} fct_u STATION_{iu} + \sum_i fcc_i CLOSE_i \le bman, \tag{25}$$

$$\sum_{fi} vcm_{fi}MILCON_{fi} + \sum_{i}\sum_{r\in N} vcr_{ir}RANGE_{ir} + \sum_{fi} vcu_{fi}UPGRAD_{fi} + \sum_{cff'i} vccv_{ff'i}CONV_{cff'i} + \sum_{i,\, u\in UA_i \text{ and } u\notin IS_i} (vct_{iu} + fct_u)STATION_{iu} + \sum_i fcc_i CLOSE_i \le btotal. \tag{26}$$

OSAF constraints accomplish four main tasks:

1. Meet facility space and condition requirements for each FAC group.
2. Ensure proper range days and KM^2 days for heavy and light unit training.
3. Set unit stationing requirements.
4. Limit up-front implementation costs.

We categorize the constraints into four types—facility, training, stationing, and one-time cost—and briefly describe each below.

a. Facility constraints

Constraints (1)–(9) ensure proper facility space for units. Constraint set (1) ensures that sufficient existing facility space exists at each installation and FAC group. If there is a shortage, MILCON or a facility conversion provides the required space. There is a reduction to a FAC group capacity when a unit occupying vapor-condition FAC space is reassigned or space is converted into another FAC type. Constraint set (2) ensures that each installation and FAC type has sufficient green-category facility space for units moved to the installation. MILCON, upgrading existing empty facilities, or FAC conversions satisfy facility shortages. Constraints (3)–(9) ensure that vapor-condition facilities vacate first, followed by other condition facilities, and then green-condition facilities. They also ensure that upgrades occur to only empty or vacated facilities.

b. Training constraints

Constraints (10)–(20) ensure that units have access to sufficient training ranges and maneuver land. Constraint sets (10) and (11) account for any training-range use above the existing capacity at an installation. Constraints (12) require new ranges to be built to satisfy any shortfall above a predefined acceptable level for a subset of range types. Constraints (13)–(15) restrict allowable range shortfall by the total Army-wide installation, and for the set S, respectively. Constraints (16)–(18) restrict allowable maneuver land KM^2 day shortfall by the total Army-wide installation, and for the set S, respectively. Constraints (19) and (20) allow light-maneuver range requirements to be satisfied at heavy ranges if the heavy capacity has not been fully used by heavy units.

c. Stationing constraints

Constraints (21) and (22) ensure that units are stationed at allowable installations. Constraint set (21) requires each unit to be stationed at one installation in its set of allowable installations. Constraints (22) ensure that units are not stationed at a closed installation.

d. One-time cost constraints

Constraints (23)–(26) limit BRAC implementation costs. They ensure that the respective implementation costs are less than the MILCON, transportation, management, and total budgets.

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References

Brown, G., R. Dell. 2007. Formulating linear and integer linear programs: A rouges' gallery. *INFORMS Trans. Ed.* **7**(2), http://archive.ite.journal.informs.org/Vol7No2/BrownDell/.

Brown, G., J. Keegan, B. Vigus, K. Wood. 2001. The Kellogg Company optimizes production, inventory and distribution. *Interfaces* **31**(6) 1–15.

Connors, G., R. Dell, W. Tarantino. 2001. Optimal stationing of Army forces model (OSAF). Final Report CAA-R-01-42. Center for Army Analysis, Fort Belvoir, VA.

Department of the Army. 2003. Real property planning and analysis system (RPLANS). Washington, D.C., September.

Department of the Army. 2004a. TC 25-1: Training land: Unit training land requirement. Fort Eustis, VA, March.

Department of the Army. 2004b. Memorandum for Under Secretary of Defense (Acquisition, Technology & Logistics). SUBJECT: 2004 Base Realignment and Closure (BRAC) Report to Congress. Washington, D.C., March.

Department of the Army. 2005. TABS Analytical Framework, TAF. Washington, D.C.

Department of the Army. 2007. AR 210-14: The Army Installation Status Report Program. Washington, D.C., April.

Department of Defense. 2005. Report to the Defense Base Closure and Realignment Commission. Department of the Army Analysis and Recommendations BRAC 2005. Vol. III. Washington, D.C., May.

Dell, R. 1998. Optimizing army base realignment and closure. *Interfaces* **28**(6) 1–18.

Dell, R., C. Fletcher, S. Parry, R. Rosenthal. 1994. Modeling army maneuver and training base realignment and closure. Technical Report NPS-OR-94-002, Operations Research Department, Naval Postgraduate School, Monterey, CA.

Ewing, P., J. Bassichis. 2005. Optimal stationing of army forces (OSAF) for base realignment and closure (BRAC) 2005. Final Report CAA-R-05-13, Center for Army Analysis, Fort Belvoir, VA.

Ewing, P., W. Tarantino, G. Parnell. 2006. Use of decision analysis in the army base realignment and closure (BRAC) 2005 military value analysis. *Decision Anal.* **3**(1) 33–49.

GAMS Development Corporation. 2007. General algebraic modeling system (GAMS). Retrieved December 15, 2007, http://www.gams.com.

GAMS/CPLEX. 2007. CPLEX 11. Retrieved December 15, 2007, http://www.gams.com/dd/docs/solvers/cplex.pdf.

Government Accounting Office. 2001. Military base closures: DOD's updated net savings estimate remains substantial. Report 07/01, GAO/NSAID-01-971. Washington, D.C.

Loerch, A., N. Boland, E. Johnson, G. Nemhauser. 1996. Finding an optimal stationing policy for the US Army in Europe after the force draw down. *Military Oper. Res.* **2**(4) 39–51.

Owen, S., M. Daskin. 1998. Strategic facility location: A review. *Eur. J. Oper. Res.* **111** 423–447.

ReVelle, C., H. Eiselt. 2005. Location analysis: A synthesis and survey. *Eur. J. Oper. Res.* **165** 1–19.

ReVelle, C., H. Eiselt, M. Daskin. 2008. A bibliography for some fundamental problem categories in discrete location science. *Eur. J. Oper. Res.* **184** 817–848.

Richards, C. 2003. Modeling unit facility requirements in an integer linear program to recommend Army stationing. Master's thesis, Naval Postgraduate School, Monterey, CA.

Richardson and Kirmse. 2004. *User's Manual, COBRA, Cost of Base Realignment Actions*. Richardson and Kirmse, Inc., Roanoke, VA.

Tarantino, W. 2002. Optimal stationing of army forces (OSAF)—21st CAV. Final Report CAA-R-02-5, Center for Army Analysis, Fort Belvoir, VA.

Tarantino, W. 2003a. Stationing the army for transformation. Final Report CAA-R-03-1, Center for Army Analysis, Fort Belvoir, VA.

Tarantino, W. 2003b. Stationing the army for transformation, Vol. II. Final report, unpublished. Center for Army Analysis, Fort Belvoir, VA.

Craig E. College, Deputy Assistant Chief of Staff for Installation Management, Department of the Army,

600 Army Pentagon, Washington, D.C. 20310-0600, writes: "I have reviewed the manuscript entitled "Optimally Stationing Army Forces" by Robert F. Dell, Lieutenant Colonel P. Lee Ewing, US Army, and Colonel Bill Tarantino, US Army (retired), and verify its accuracy. For BRAC 2005, I led The Army Basing Study, the group responsible for generating the Army's recommendations for closure and realignment, and coordinating all Army BRAC 2005 analysis.

"All authors were personally involved with the analysis described in the article and Bill was my Chief of the Army BRAC 2005 Analysis Division, responsible for all analyses including OSAF related work. OSAF was one of a portfolio of models that I used to help us examine different closure options and develop our recommendations. OSAF was the model of choice to analyze complex interactions between multiple realignment options."